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Status Report

THERMAL PROCESSES FOR HEAVY OIL RECOVERY

Project BE11B, Milestone 4, FY89

By D. K. Olsen

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ABSTRACT

This status report summarizes the research conducted in FY89 under each of the three tasks in project BE11B Thermal Processes for Heavy Oil Recovery and completes milestone 4 of this project. Multiple-zone steamflood experiments were conducted using mobility-control agents to divert steam in heavy oil. The effects of temperature on capillary pressure and wettability of heavy oil in sandpacks indicate increasing wettability with temperature. Results of this research include: development of a numerical thermal simulator for laboratory applications; indications that wettability increases with temperature; and evaluation of surfactants and emulsions as steam diverters. A numerical simulator has been developed from fundamental principles to assist in the analysis of laboratory steamflood experiments.

EXECUTIVE SUMMARY

Based upon the analysis of the progress at midyear FY89, modifications to the FY90 work plan were made which accommodate anticipated results given in this report. Results and conclusions from the FY89 BE11B research on Thermal Processes for Heavy Oil Recovery are listed below in order of priority.

1. The development and testing of a numerical thermal simulator for assisting in laboratory steamflood experiments have progressed to the point where a topical report is being prepared for delivery in FY90.
2. The capillary pressure-wettability of porous media directly affects steamflood recovery of heavy oil.
3. Methods of packing a two-dimensional (2-D) steamflood apparatus have been developed to simulate zones of various permeability. However, additional data from steamflood experiments are needed to evaluate the simulator that has been developed for analyzing and predicting steamflood performance.
4. Modifications made to the current 2-D steamflood apparatus are insufficient, and a new high-pressure, thin-wall 2-D apparatus needs to be designed (scaled) and constructed to avoid current problems of high heat loss and heat conduction along the sides of the thick-wall model. This design factor has retarded experiments used to evaluate steam diverters because the steam front is nearly vertical, producing a piston-like displacement in the model.

5. For evaluation of surfactants used as steamflood steam diverters, foam should be generated outside the model. The model must have adequate oil saturation at the time of diverter injection to ensure that oil is available for diversion and that differences in surfactant performance can be based upon differential pressures and oil production.

INTRODUCTION

The National Institute for Petroleum and Energy Research (NIPER) Annual Research Plan for FY89 describes research for project BE11B, Thermal Processes for Heavy Oil Recovery.[1] As compared with previous status reports, which were brief summations of the work conducted in this project, this status report describes results and the methodology used in individual tasks within this project. Topical reports on specific, well-defined areas of work will be forthcoming when an area of work warrants coverage. Based upon the analysis of the progress at midyear FY89, modifications to the FY90 work plan were made which accommodate anticipated results described in this report.

OBJECTIVES

The objective of the FY89 research program on thermal processes for heavy oil recovery has been to improve the understanding of basic mechanisms responsible for heavy oil production using steam. Application of chemicals for emulsion breaking or viscosity reduction in cyclic steam and application of chemicals for steam diversion in steamflooding are two methods used to improve heavy oil production. The FY89 research program objectives have been divided into three parts:

1. Investigate the effectiveness of mobility-control agents in diverting steam from a zone of higher permeability to a zone of lower permeability;
2. Evaluate the effect of temperature on capillary pressure/wettability measurements of heavy crude oils in a sandpack; and
3. Compare predicted values with laboratory-measured values of steamflood performance.

BACKGROUND

Heavy oil as used in this research is <20° API gravity, but oil gravity is not the only property that limits heavy oil production. Heavy oils have in situ viscosities from < 1,000 to >1,000,000 mPa•S at reservoir temperature. A recent review of heavy oil production for those oils whose viscosity is >2000 mPa•S has been published by Selby, Alikhan, and Farouq Ali.[2] Currently steamflooding is the primary method used for heavy oil recovery. More oil is produced by thermal methods, cyclic steam, and steamdrive than any other enhanced oil recovery (EOR) process, and thermal EOR contributes 6% of the domestic oil production.[3-4] Although the United States produces more heavy oil by thermal methods than other countries,[4] the United States has only a small fraction of the world's heavy oil reserves.[5] However, technical and economic problems with steam recovery of heavy oil remain unsolved.

A major challenge is controlling steam mobility and improving sweep efficiency in reservoirs. This has been the main NIPER objective for additive or diverter evaluation since 1985. Methods were developed to determine the stability of foaming surfactant additives and the effect of these additives on steamflood oil recovery.[6] In addition to foams, surfactants are likely to produce emulsions, and these emulsions may be important in changing the flow of steam through porous media.

NIPER constructed a partially scaled high-pressure, thick-wall, 2-D steamflood model to study steam diversion in 1985.[7] This model was designed to allow researchers to observe vertical steam front profile changes resulting from the introduction of additives.[8] Similar experiments (at steam temperature or lower) with foams have been conducted by other workers,[9-11] and in the presence of mineral oils.[12] During FY86, the NIPER 2-D steamflood apparatus was designed and constructed, pressure tested, characterized, and used to conduct an initial investigation on the profile modification of steam fronts, with and without foaming surfactants.[7] During FY88, several operational variables were investigated to determine the effect of these variables on the effectiveness of a surfactant foam for steam mobility control.[13-14]

In many field applications, steam is injected simultaneously into several oil zones, each having different fluid and rock properties. Although the tendency of steam to rise to the top of a zone (gravity override) is known and was investigated at NIPER during FY87[14] and FY88,[15] the tendency of steam to selectively enter one zone over another due to favorable permeabilities has not been thoroughly evaluated.

The experimental work for FY89 has included the evaluation of a steam foam system under more realistic situations. Steamflood experiments were conducted using NIPER's 2-D steamflood physical model. This model contained multiple sand zones, each with different permeabilities. Ideally, an effective mobility-control system should alter the flow of steam into zones not originally contacted by steam, such as zones of lower permeability.

In addition to steamflood experiments, experimental work for FY89 has included an initial investigation of the effect of capillary pressure and wettability on high-permeability sands. Related work under DOE project BE11A showed a significant dependence of wettability on temperature.[16] An evaluation of capillary pressure/wettability changes for heavy oil is applicable to a greater number of cases because most of the crude oil recovered by steam is heavy oil, and heavy oils contain a higher percent of components that can cause rock surfaces to become oil-wet.

Experimental results on heavy oil steamflood experiments performed from FY85 through FY89 will be compared with predicted values based upon fundamental processes predominate in laboratory experiments and should indicate similarities and differences that exist between laboratory experiments and field applications.

SCOPE OF WORK

The three tasks, as described in the scope of work described in the NIPER FY89 Annual Research Plan[1] for BE11B, are listed below along with their start and completion dates:

Task 1. Conduct multiple zone steamflood experiments using crude oil and mobility-control agents. (Start date: October 1988. Completion date: September 1989.)

Work completed in FY89 isolated and characterized several operational variables important to the effectiveness of steam foam surfactants. These operational variables were evaluated according to oil recovery efficiency and reduced gravity override effects that resulted from the addition of a mobility-control agent. However, many injection and production wells in the United States and elsewhere communicate simultaneously with more than one producing zone. As a result, the amount of oil recovered depends upon the mobility of the steam in each zone relative to the other zones.

Experimental work performed in FY89 under this task included the evaluation of a steam foam system under more realistic conditions than those of steamfloods conducted previously. Steamflood experiments were conducted in NIPER's 2-D steamflood physical model, which contained multiple zones of differing permeabilities. Ideally, the mobility-control systems tested should be effective in altering the flow of steam into zones not originally contacted by steam, such as a zone of lower permeability. Since these types of experiments have not previously been conducted at NIPER, initial activities under this task included the development of an acceptable experimental procedure for conducting these experiments. This procedure includes methods for determining exact dimensions of individual zones, permeabilities of individual zones, and fluid flow rates in individual zones. All of these activities are nontrival, and they were expected to consume most of the allotted time for this task.

Task 2. Evaluate the effect of temperature on capillary pressure and wettability on a system containing heavy crude oils in a sandpack. (Start date: October 1988. Completion date: September 1989.)

During FY87 and FY88, work done for the related DOE project, BE11A, determined that increasing temperatures corresponded with increases in water-wet conditions for Berea sandstone cores using light crude oils. However, most of the crude oil recovered by steam in the field has been heavy crude oil rather than light crude oil. This task of evaluating temperature effects for heavy crude oil systems is included in the FY89 annual plan. No published reports have included data on heavy oils, despite the large quantity of heavy oil produced by steam. Preliminary work was conducted in FY88[15] to develop a method for measuring the wettability of a sandpack containing heavy crude oils. This developmental work was continued under this task, and the method developed was used to evaluate the effect of temperature on capillary pressure and wettability of a sandpack.

Task 3. Compare experimental steamflooding information obtained during FY84 through FY88 with predicted values based upon fundamental principles. (Start date: October 1988. Completion date: September 1989.)

Work similar to this task has been conducted in FY88 and FY89 under the related DOE project, BE11A. This task was added to DOE project BE11B to take advantage of the information learned about steamflooding light crude oils in the 2-D steamflood model. The strongest method for deriving conclusions from experimental results requires a comparison of experimental results with expected values calculated from equations that represent known or proposed theoretical principles. Task 3 was included to make this comparison.

As with the related BE11A project, the numerical thermal simulator developed in FY88 was used to conduct extensive comparisons of predicted values with measured values, and sensitivity studies were used to help direct optimum selection or operational parameters of future steamflood experiments. Measured residual oil saturation profiles and oil production profiles were compared with predicted values. However, the simulator developed in FY88 is incapable of evaluating surfactant foam systems used for mobility control. The addition of this capability to the simulator was not expected during FY89. The completion of this task provides a better understanding of many laboratory experiments conducted from FY85 through FY89 at NIPER.

ACKNOWLEDGMENTS

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CHAPTER 1. - MULTIPLE ZONE STEAMFLOOD EXPERIMENTS, TASK 1.

OBJECTIVE

The objective of this task is to investigate the effectiveness of mobility-control agents in diverting steam from a zone of higher permeability to a zone of lower permeability.

BACKGROUND

The use of mobility-control agents for steam diversion to improve sweep efficiency of cyclic steam or steamdrive is common practice. Several reviews have been presented recently on both laboratory and field assessments of the technology. Field applications and the underlying phenomena and laboratory work have been reviewed by Islam, Selby and Farouq Ali.[1] Hirasaki[2] focused on field application of steam foams with examples from reported field pilots and then focused on process mechanisms and the understanding of mechanisms of foam flow in porous media.

To establish the state-of-the-art for commercial steam diversion with foam, published data, table 1, were analyzed. These data list the method of application and the cost of chemicals required per barrel of incremental oil produced. These costs are both in terms of pounds of chemical used and in dollars of the chemical used per incremental barrel. The classifications are those suggested by Eson and Cooke[3] who presented a summary description of the floods and economics. The tabulations are listed by name of the first author of the paper or the supporting institution.[4-12]

Research at NIPER on steam diversion in heavy oils has approached the problem from two different directions. French et al.[13-19] worked to develop emulsions as steam diverters -- both in situ and surface-generated emulsions. Madden, Strycker, Sarathi, and Roark have worked on foams composed of surfactants and an inert gas as a method to divert steam to areas that have not been swept.[20] This research has included screening surfactants and laboratory 2-D displacements of crude oils with steam and steam with additives.[21]

EXPERIMENTAL PROCEDURES

Materials and Equipment

Studies of mobility-control agents to divert steam were conducted in the NIPER 2-D, high-pressure, thick-wall, physical model which is partially scaled. The model represents a vertical section through a reservoir. A fully scaled model would provide a better means of evaluating the processes under investigation in the laboratory; however, it is not possible to scale all thermal, geometrical, physical and chemical parameters simultaneously for this process.[1] As constructed, the NIPER 2-D steamflood apparatus is partially scaled and is designed to simulate one-quarter of a 2.5-acre, inverted 5-spot with a scaling factor of 117. The geometric similarity requirement for pay thickness was relaxed to emphasize override phenomena. High-temperature, high-pressure experiments were performed with reserving fluids (crude oil and brine) and representative porous media (sieved quartz sand or crushed and sieved Berea sandstone) under simulated reservoir conditions. Model flow rate scaling was arbitrary because of equipment limitations. The test element was designed to study the response of a similar formation element to the process under investigation. It is expected that experiments of this type in essentially two-dimensional systems will yield information necessary for the understanding of underlying mechanisms and for the development of numerical models of steamflooding and of the diversion of steam with added chemicals.

The NIPER 2-D steamflood model has internal dimensions of 1.5 x 5.75 x 22.5 inches. The model is internally coated with 0.5 inch of high-temperature ceramic (Zircon cement) and has 3/8-inch steel walls with three steel reinforcement sections along the side to reduce the bowing of the sides of the model when used in the normal pressure range to 250 psi. The model is externally covered with 4 inches of high-temperature glass fiber insulation (Fiberfax) to reduce heat loss. The 2-D model is shown schematically in figure 1, and the overall steamflooding apparatus is shown as a schematic in figure 2.

The model is equipped with inlet and outlet distribution plates with filter screens which allow fluids to be injected and produced from either the top or bottom of the sandpack or both top and bottom. There is another set of distribution plates that allow injection or production across the entire cross section. These plugs are covered with 500 mesh screen to reduce the production of solids that plug backpressure regulators.

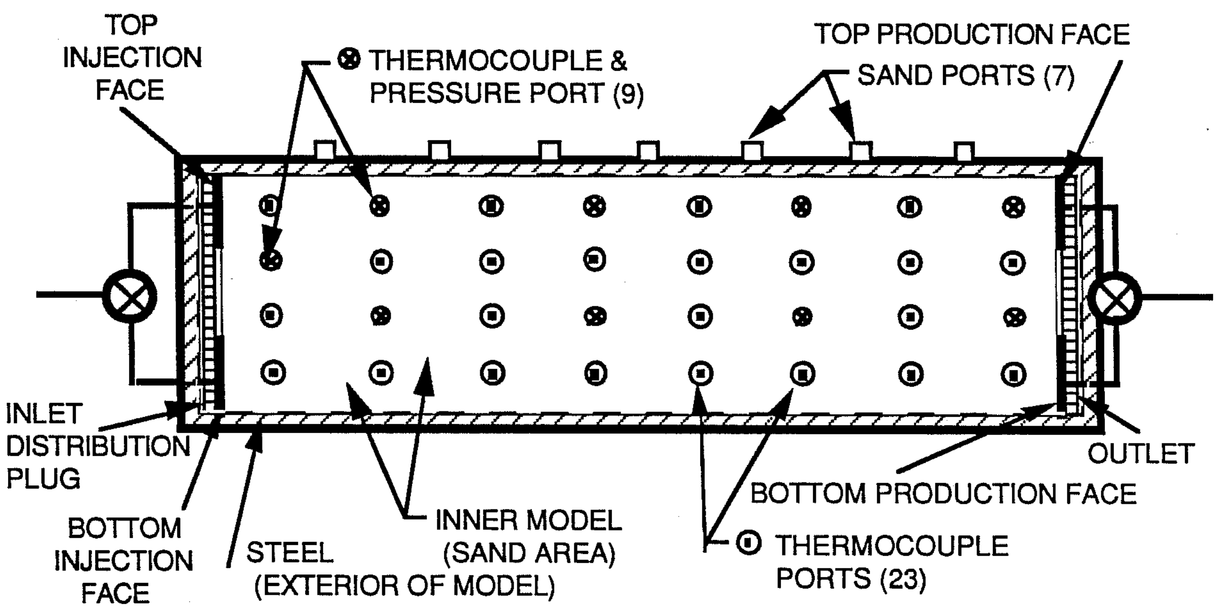

FIGURE 1.- Schematic of two-dimensional steamflood model.

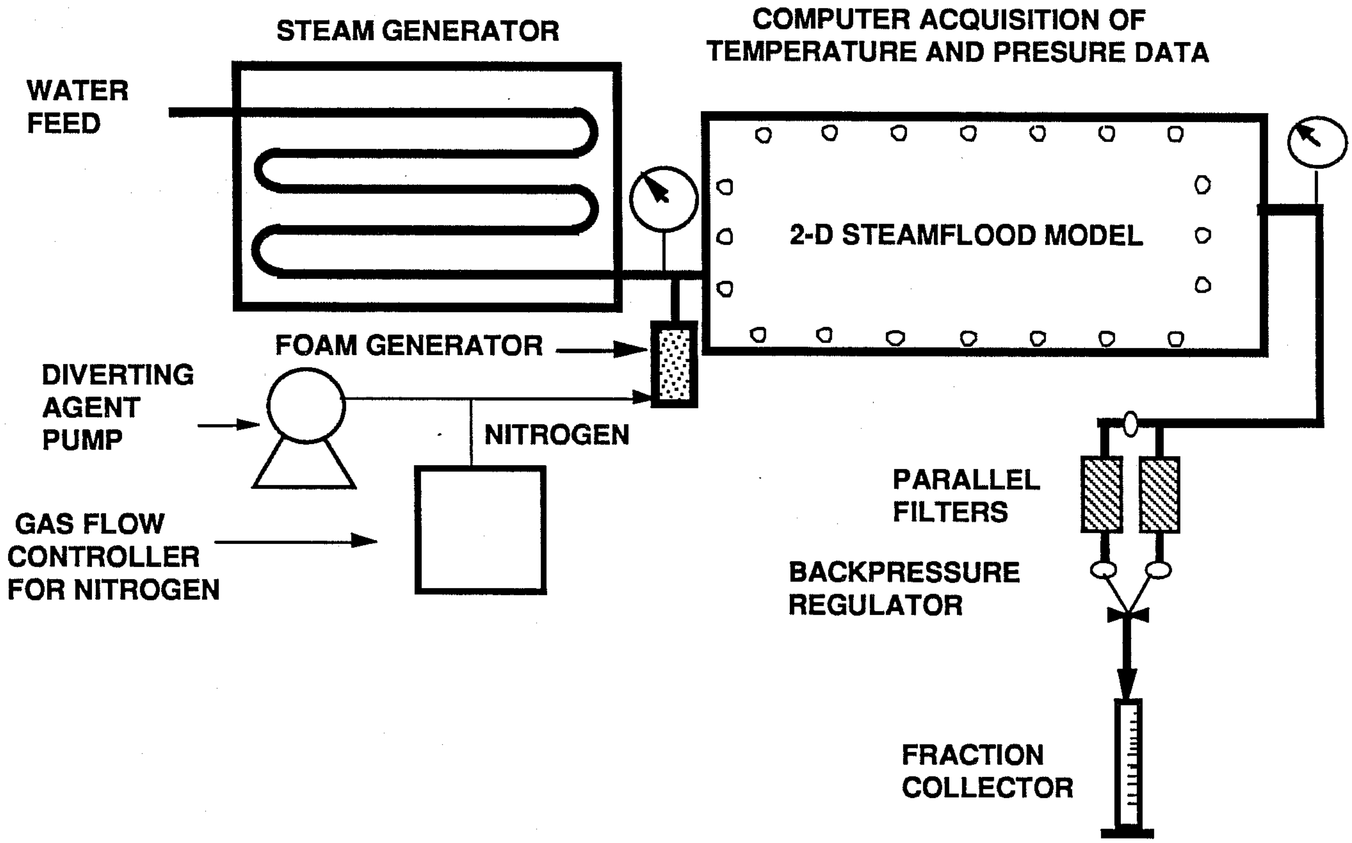

FIGURE 2.- Schematic of steamflood assembly.

Temperature measurements are taken from an array of 32 ports consisting of four rows and eight columns. Nine of these ports also double as pressure taps where Druck (model DPI 420) pressure transducers are connected to monitor pressure along the sandpack. An IBM XT computer interfaced with a Keithley Series 500 data-acquisition system collects and stores the temperature and pressure data. Differential pressures across the 2-D model are measured by Validyne transducers (model DP215) connected to strip chart recorders. Validyne CD233 digital demodulators allow visual monitoring of pressure.

Pressure in the model is maintained with a Badger pneumatic control valve (regulated with a Doric DC7100 Microprocessor) which can be set within 0.5 psi of a desired backpressure up to 600 psig. The built-in, self-tuning feature in the microprocessor allows optimum opening of the valve. A constant flow through the entire system can be obtained with this backpressure regulator. Solids not removed at the outlet to the 2-D model by the screens are removed by Nupro in-line filters (60 micron). These are set up in parallel to allow flow to be diverted to a standby filter while filter elements are cleaned or replaced as solids plug the backpressure regulator. Produced fluids pass through a water-cooled condenser before being collected by manual switching of graduated cylinders or the use of a fraction collector (Gilson FC-100 microfractionator). The manual switches allowed variable volume collection while constants volume (<10 cm^3) and finer oil/-water ratios were available from the use of the fraction collector.

Steam is generated by pumping deionized water with a Milroyal (model A) metering pump through a (Lindberg 54571) tube furnace containing stainless steel tubing that has been coiled around a stainless steel pipe to increase heat transfer. The furnace is equipped with a controller which allows local control or remote control through the computer. The temperature in the furnace can be controlled from ambient temperature to 1,000° C. A constant supply of water for the pump reservoir is assured by means of a (Dyna-Sense 7188) automatic level controller. Steam generated from this assembly is superheated at the furnace exit. Heat losses in the steam lines between the furnace and the 2-D model results in high-quality saturated steam at the point of injection into the model. Steam is introduced into the model at 385 °F. The piping is insulated with 5 inches of Fiberfax, and the steam supply lines have an additional aluminum reflective wrap to reduce convective heat losses and help to maintain heat within the model.

Liquid additives for the 2-D model are injected with Milroyal (model D) or Isco (model 2300 HPLC) pumps while gases are injected through a Teledyne vapor mass flow controller (model CPR-1A) that is capable of controlling gas flow rate to as low as 0.1 cm^3/min at standard temperature and pressure. Spring-loaded check valves are placed in the system to act as safety pressure relief devices.

Produced fluids are usually highly emulsified, and this year chemical treating was used to produce clean oil and water which greatly improve the mass balance of the experiments. The Kern River crude was broken using a combination of chemical additives specifically blended for this heavy oil by Chem Link.

The packing material for the 2-D model is specified in each of the runs. Properties of the sands and sieve size are listed in table 1. To help reduce the permeability when crushed Berea sandstone was used, at least 50 pore volumes (PV) of distilled water was injected, and some of the clays were swelled.

Surfactants partition both into the aqueous phase and oil phase and thus a series of studies were conducted to determine the solubility of Chaser 1020 in two crude oils at 350° F in an attempt to define the concentration level necessary for foam generation in the 2-D model. Solutions of Chaser 1020 were heated in pressure bombs containing both field brine and a 50/50 mixture of brine and oil. Surfactant analysis by three-phase titration method of the aqueous phase was conducted after shaking and heating the pressure bombs for 48 hours. The results indicate that the surfactants remained in the aqueous phase rather than partitioning into the oil as shown in table 2.

TABLE 1. - Properties and specifications of the quartz sand (crushed Berea sandstone) used in the 2-D steamflood model

Sieve pan mesh size	Weight percent retained by screen			
	Coarse	Medium	Fine	Crushed Berea
20	3.26	0.00	0.00	0.00
40	90.15	0.22	0.02	0.00
70	6.48	5.51	1.07	3.22
100	0.10	32.35	3.29	82.82
120	0.01	13.46	10.96	7.49
140	0.00	25.92	33.35	4.44
170	0.00	11.23	23.51	0.62
200	0.00	6.69	17.07	0.20
pan	0.00	4.62	10.73	1.21

TABLE 2. - Solubility of Chaser 1020 in various crude oils, %.

Oil	Initial, concentration, ppm	Aqueous Final Concentration, ppm	Final concentration, % original
Kern River	5,000	4,700	94
Round Mtn.	5,000	4,800	96
New London	5,000	4,774	95
Brine only	5,000	500	100

EXPERIMENTAL RESULTS AND DISCUSSION

Analysis of Published Field Tests of Steamflood Diverters and Their Costs

Table 3 shows a broad spectrum of cost per incremental barrel of oil. When these costs are added to steam-generating and lifting costs for heavy crude oil that usually sells for less than 70% of the price of West Texas Intermediate or of other benchmark light oils, the economics of operating a steamflood focus on a low profit margin, and steam-diversion projects can easily become uneconomic. Thus, application of cost-effective steam diverters is a critical parameter as well as the cost of steam. A recent telephone survey of operating costs showed that the energy source to generate steam is the principal factor affecting economics with Kern County heavy oil production costing $8.00/bbl if the steam was cogenerated to produce steam for EOR and to produce electricity; with steam generated from natural gas, lease crude cost $9.00/bbl, and when lease crude was used as the fuel the cost increased to $10.00/bbl.[22]

TABLE 3. - Analysis of published field applications of steam foam diverters - use and cost

Ref.*	Operator	Field	Sand	Treatment	Surfactant used per incremental bbl lb/bbl	Surfactant used per incremental bbl $/bbl
Greaser[4]	Getty	Kern River		Slug	0.6	0.49
Farrell[5]	Petro Lewis	Kern Front	–	Slug	2.0	1.80
Doscher[6]	Santa Fe Energy	Midway Sunset	–	Cont.	0.7	0.57
	Conoco	Cat Canyon	–	Cont.	Ineffective surfactant due to high temperature[3]	
	Texaco	San Ardo	–	Cont.	Too small a slug and too short a pilot period[3]	
Palzek[7]	Shell	Kern River	Mecca	Cont.	7.1	5.44
			Bishop	Cont.	15.1	11.58
Mohammadi[8]	Unocal	Santa Maria	–	Cont.	8.7	11.75
Mohammadi[9]	Unocal	Midway Sunset	–	Cont.	5.8	4.5
SUPRI[10,11]	Petro Lewis	Kern River	–	Semi-cont.	3.3	4.42
Ploeg[12]	Chevron	Midway Sunset	–	Semi-cont.	1.0	1.35
Ploeg[12]	Chevron	Midway Sunset	Monarch	Semi-cont.	3.3	4.42

* First author of paper

Two-Dimensional Steamflood Model Operation and Heat Loss

The NIPER 2-D model was not intentionally designed as a partially scaled model but rather for the evaluation of steam override and for the evaluation of steam diverters. Analysis of the 2-D model shows that heat transfer along the sides of the model are largely responsible for the near vertical steam fronts that are generated in the model, as shown in figure 3. These fronts are less vertical when two or more layers of different permeability are packed into the model, but as the steamflood progresses, even multilayer sandpacks show a nearly vertical thermal front with little steam override. Since our data collection system has recorded the thermal front progression on all previous 2-D steamfloods performed in this laboratory, the analysis indicates that the deficiency in the model is not correctable by higher steam injection rates within pressure limitations of the model; therefore, a new 2-D steamflood model is needed.

Differential pressures between ports within the model have been routinely obtained with the nine Druck pressure transducers. These 0-500 psi transducers measure the difference in pressure between inside the model (250 psi backpressure on the outlet) and the atmosphere. Small variations in pressure within the model are within the ± 5% accuracy of the transducers and are of marginal use when combined with pressure pulses generated in the model by the backpressure regulator opening and closing. Future 2-D steamflood models should incorporate more accurate pressure transducers such as the Tobar pressure transducers currently used on other foam research projects at NIPER.

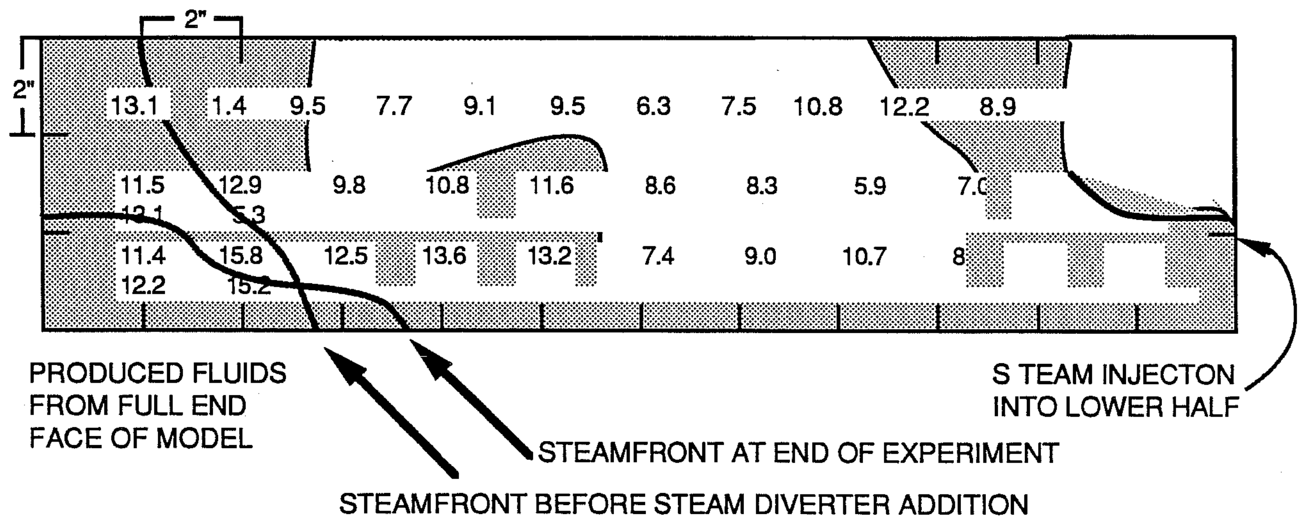

FIGURE 3. - Typical thermal fronts as monitored by thermocouples at the point where one of the thermocouples on the outlet is within 10° F of steamflood temperature.

Variations in the mode of operation were tried to generate significant gravity override in the 2-D model. The most effective method was packing the model with sands of different permeability and using a montmorilinite clay to separate the layers. Brine permeability measurements conducted at the start of the steamflood experiments indicate communication between layers, but within the higher permeability layer, the steam front moves much like a piston in displacing the oil from steam injector to producer as monitored by the thermocouples in the model. Closely spaced Dean Stark analysis of the sand (as shown by the oil saturations in figure 3 where the darkened area represents an oil saturation > 10%) and photographs of the model after opening the model show that there are areas in both single-layer and multiple-layer models where the steam-swept zones, as indicated by the thermocouples, have lenses of higher residual oil saturation.

The injection of diverter in the 2-D model has traditionally occurred when any single thermocouple in the row nearest the producer comes within 10° F of the steam inlet temperature. This was assumed to be steam breakthrough as thermocouples on the outlet line quickly attained steam temperature shortly after this point in the steam injection. This means that most (>80%) of the model in most cases has been swept by steam. Thus, addition of steam diverter has had little oil remaining to produce, and only a small percentage of the OOIP (<5%) is produced as a result of diverter addition. Small pore volume (PV) additions of diverter that are typical of field scale (less than 10% PV) produced results that are nearly undetected in our model although steam may have been diverted around the emulsion or foam bank. Thus, several 2-D steamfloods conducted over the past few years and this year were large PV or continuous injection of diverter.

In previous years, and most of this year in steamflood tests, surfactants and inert gas were co-injected into the steam line or the upper half of the model or sequentially injected. The resulting pressure buildup has always been less than that reported by others evaluating the same surfactant in their steamflood models. The surfactant solution must traverse part of the model to generate foam (more distance is required with more permeable sandpacks to generate a foam), and this behavior is reflected in the low differential pressures attained within the model. Similar problems of correlating surfactant behavior, pressure generation across the model and incremental oil recovery were reported in the NIPER 1987 Annual Report[21] when 1-D sandpacks were used. This year, several variations of external foam generators were used in later floods and significantly higher pressure drops across the model were produced. The foam generator found most useful was a section of 4-inch fired Berea core valved into the steam line. This enabled the mixing of the surfactant and nitrogen and generation of the foam before the foam is added to the steam path and injected into the 2-D model.

Two-Dimensional Steamflood Tests - Emulsions

NIPER has pursued research on the use of oil-in-water macroemulsions for steam diversion since 1984. This year, testing of the emulsion system developed by French[19] was continued. Recently, Decker and Flock[24] of Canada published a paper entitled "Thermal Stability and Application of Emulsion Composed Blocking Agents for Steamflooding," which also details their use of emulsions for steam diversion. Two 2-D steamflood tests were conducted to determine if the emulsion could divert steam or develop an increased differential pressure across the 2-D model or affect the oil production by changing the oil-water ratio. Previous emulsions had been tested in single and multiple layer 1-D low-permeability (300 md) fired Berea cores where large pressure drops were generated within the first few inches of the injection face.[19] This year's work was to evaluate the response in porous media that would better represent the permeability of Kern River sands, >1.5 darcies.

The emulsion developed by treating Kern River crude oil with sodium hydroxide is a thermally stable, highly dilutable emulsion of average diameter of 6 microns. Based on recent filtration studies by Pautz, Crocker, and Walton,[25] and the standard rule of thumb (plug at <1/7 pore diameter) for predicting formation damage, the emulsion would be expected to pass through a matrix of permeability >8 darcies; thus, the first test in the 2-D model was conducted at the end of a surfactant foam experiment to evaluate the transport time and thermal stability of the emulsion.

The first steamflood used two layers of packed unconsolidated sand. The top layer was a high-permeability zone of 25.8 darcies, with the bottom being a lower permeability zone of 10.0 darcies. Oil recovery by steam totalled 75.0% of the original-oil-in-place (OOIP) before additives were injected. A 5% pore volume (PV) and a 10% PV of 0.1% active Chaser SD1000 and nitrogen were injected as slugs to act as diverting agents. This was followed by another 10% PV slug of SD1000 but with continuous nitrogen flow. Some blocking by the foamer was observed, and the overall pressure drop across the 2-D model increased by 10%, as shown in figure 4. These three surfactant slugs yielded an additional oil recovery of 10.4% of the remaining oil. Two alkaline emulsion slugs, one 25% PV and one 10% PV, were injected in an attempt to produce more oil. While no increase in pressure drop was detected, 5.8% of the remaining oil was produced. The emulsion slug was found to be delayed by 6% PV as compared to a water-soluble disodium fluorescein tracer injected 1 hour after the emulsion. The emulsion was analyzed by visual inspection under a microscope and compared with the injected emulsion. Eighty-two percent of the emulsion has sizes still within one standard deviation of the bell-shaped curve centered at 6 microns, the emulsion size that was injected.

The second 2-D steamflood (fig. 5) was conducted on a single layer of crushed Berea sandstone in an attempt to achieve lower permeability. The initial permeability was reduced from 6.0 to 1.3 darcies by pumping 150 PV of deionized water through the model. Oil recovery by steam totalled 81.4% of the OOIP. A 24% PV alkaline emulsion slug was then injected to divert steam flow into zones of higher oil saturation. An increase of 20% in pressure drop across the sandpack was observed, indicating that diversion of steam was occurring. Oil recovery totalling 15.5% of the remaining oil was obtained with the emulsion.

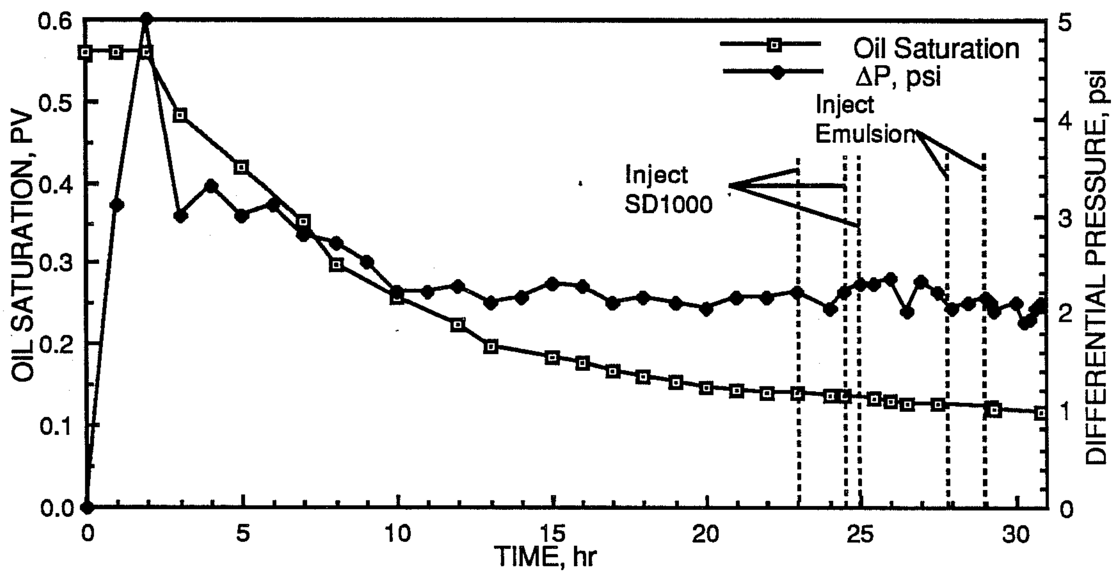

FIGURE 4 - Two-dimensional steamflood of Kern River crude oil and test of steam diverters.

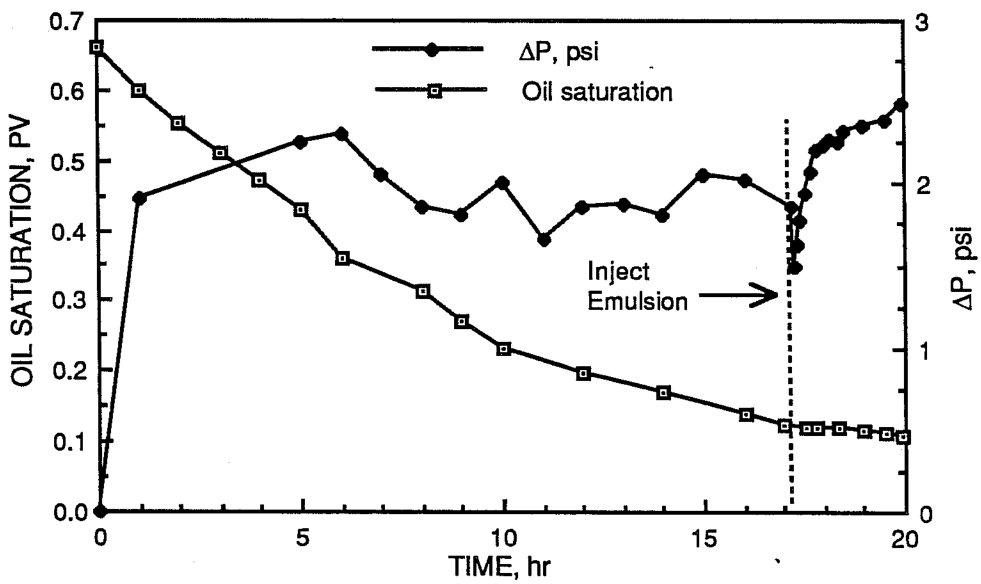

FIGURE 5 - Two-dimensional steamflood with emulsion steam diverter on Kern River crude oil.

From oil displacement experiments using the emulsion blocking process and under conditions used for these evaluations, the technique looks promising. However, because of the low oil saturation at the time of emulsion injection and the large volume of the model that had been swept by steam at the point of emulsion injection, the 24% PV slug was insufficient to adequately test the diverting capability of the emulsion. The emulsion blocking process would probably succeed only in those areas where the permeability is sufficiently low to the extent that the emulsion plugs the formation somewhat like plugging a filter. When applied to higher permeability formations, the emulsion would be transported as was shown in the first 2-D test. The emulsion formulation was found to be highly dilutable and thermally stable such that it can survive direct injection into the steam line at 380° F and transport through the 2-D model. However, stable emulsions of larger diameter need to be formulated if the Kern River formation, with it's higher permeability, is the target for a field experiment.

Two-Dimensional Steamflood Tests With Foams

This year, a series of steamflood displacement tests was conducted with surfactants as foamers to evaluate surfactants as diverters. The experiments used NIPER's 2-D steamflood model packed to form either one layer or two layers. With two layers, two sizes of quartz sand were used to yield a top layer with very high permeability (25 darcies), a clay layer for the barrier, and a bottom layer with high permeability (10 darcies). California Kern River crude oil, 13° API, was used as the hydrocarbon, and the diverters tested were Chaser SD1020 and Chaser SD1000. Another set of 2-D steamfloods was conducted to test Chaser SD1020 as a diverter in a two-layer sandpack, with and without Round Mountain crude. The oil-free sandpack was used in an attempt to generate and propagate foam across the entire model and measure pressures in the 2-D model such that they could be compared with the product literature supplied by Chevron Chemical.[25] The steamfloods were conducted by injecting steam into the bottom half of the 2-D model and producing from the full face of the model on the opposite end.

Steamflood performances of the diverters were tested. Overall pressure differences between the production end and the injection end of the 2-D model (ΔP), both before and after the injection of surfactant, are shown for Chaser SD1020 in figure 6. An increase in Δp of 25% was observed, indicating that some diversion of steam was occurring within the model which was also reflected by an increase in the oil-water ratio in the produced fluids.

Table 4 shows the performance of three of the diverter systems injected, including the emulsion system that was injected after the Chaser SD1000 diverter.

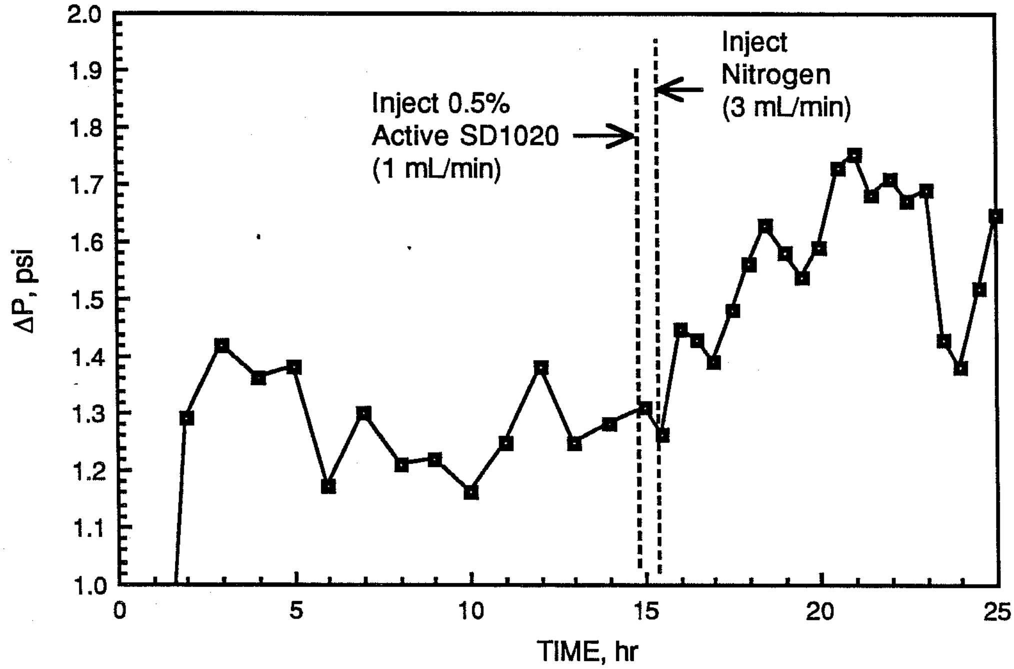

FIGURE 6. - Overall pressure drop before and after injection of Chaser SD1020 during two-dimensional steamflood.

TABLE 4. - Steamflood performance of diverting agents in recovering Kern River crude oil

	Chaser SD 1020 [1]	Chaser SD 1000[2]	Emulsion[3]
Permeability, darcies			
Upper layer	30.5	25.8	–
Bottom layer	7.6	10.0	–
Average final oil saturation, %	–	–	–
Upper layer	3.3	11.3	–
Bottom layer	11.9	12.4	–
Maximum pressure drop, psi	2.70	2.35	–
Oil saturation, (S_o, %)	67.1	56.1	–
So after steam breakthrough	25.7	25.0	–
So after 5% PV diverter	22.3	24.2	–
So after 10% PV diverter	17.1	23.5	–
So after 10% PV diverter		23.0	–
So after 20% PV diverter	15.3	–	–
So before emulsion	–	–	22.4
So after 25% PV emulsion	–	–	22.1
So after 10% PV emulsion	–	–	21.8
Surfactant conc. injected, %	0.5	1.0	2.5

1 Chaser SD1020 was injected with continuous nitrogen injection.
2 Chaser SD1000 used nitrogen injection only when the slugs were being pumped into the model with the exception of the second 10% slug where continuous nitrogen was used.
3 No nitrogen was used during the emulsion portion.

In an attempt to determine why the oil production with diverters from the 2-D model was so low and why the pressure drop across the model did not develop the hundreds of psi reported by Chevron researchers in their tests of Chaser 1020 with Kern River oil,[26] results of previous 2-D steamfloods were analyzed. Typically our oil saturation at the point of diverter addition is low (typically <15% OOIP), and the steam swept region is large as compared to Chevrons experimental conditions.[27] Figure 7 shows the results of a steamflood conducted to test the performance of Chaser SD1020 by pumping a series of surfactant slugs after steam had reached the production end of the 2-D model. Steam was halted during the rapid injection of the surfactant slugs and then resumed. An increase in the pressure drop within the 2-D model was not observed for either the 5 or 10% PV slugs of 0.5% active surfactant concentration but was observed for the 20% PV slug of 0.5% concentration and the 5% PV slug of 1.0% concentration. After each injection, there was a delay of as much as 3/4 PV before pressure developed across the model. This prompted the development of an external foam generator which could inject foam directly and continuously, if necessary, into the steam port. Results of experiments using this foam generator are being analyzed.

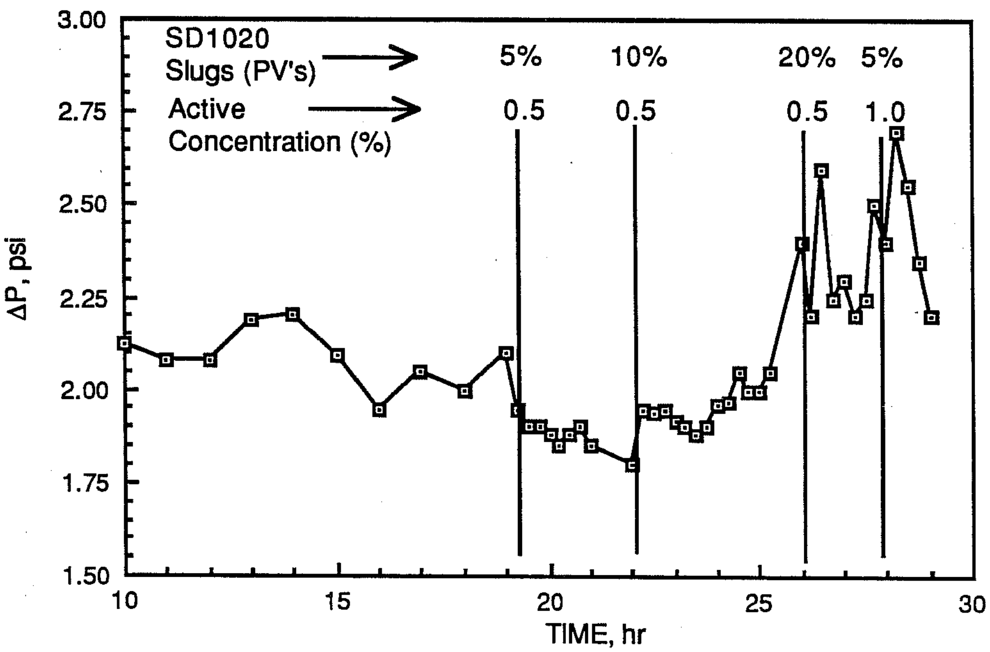

FIGURE 7. - Overall pressure drop during a two-dimensional steamflood for a series of injections of Chaser SD1020.

CONCLUSIONS AND RECOMMENDATIONS

Based upon the analysis conducted this year of the 2-D steamfloods with diverters and those conducted in previous years, limitations imposed by the design and operation of the 2-D model impair the evaluation of steam diverters. Changes in operation, such as generation of the foam external to the model and injecting directly into the steam line and running at higher steam rates have improved the performance. Modification of the backpressure regulator to open and close with less pressure pulse across the model and the use of pressure transducers that more accurately measure the differential pressure between ports could be undertaken, but heat transfer along the side walls governs the performance of the entire model. We recommend that the 2-D model be rebuilt by conducting a program that scales, designs, and then builds a thin-wall model with the design based upon a series of well designed experiments. The design should accommodate other uses of this model such as evaluation of gravity drainage or chemical flooding in this new 2-D model.

Since all experimental runs are not shown in this report, it was observed that Chaser 1020 performs better in the 2-D model than Chaser 1010 as a steam diverter, even within the limitations of the 2-D model. Emulsion blocking has potential for steam diversion if the emulsion can be formulated such that it plugs much like a particle in porous media.

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CHAPTER 2. - EFFECT OF TEMPERATURE ON CAPILLARY PRESSURE AND WETTABILITY OF SYSTEMS CONTAINING HEAVY CRUDE OILS, TASK 2.

OBJECTIVE

The objective of this task is to evaluate the effect of temperature on capillary pressure and wettability with heavy oil using a sandpack.

BACKGROUND

During FY87[1] and FY88,[2] work performed for DOE on the related project, BE11A, determined that increasing temperatures corresponded with increases in a water-wet condition for Berea sandstone cores using light crude oils. However, most of the crude oil commercially recovered by steam has been heavy crude oil rather than light crude oil. This task was performed to determine the effect of temperature on capillary pressure and wettability using heavy crude oil in a sandpack. Preliminary work in late FY88 resulted in a system that enables the use of unconsolidated material in the centrifuge for capillary pressure or wettability tests. However, several problems were encountered when attempting to evaluate these experiments on unconsolidated material. The biggest problem appears to be that of packing each core consistently. The experiments need to evaluate capillary forces independent of the packing; thus, a method has been developed that provides consistently packed cores. The second problem involves evaluation of data using our capillary pressure computer program developed in FY88.[2] Analysis indicated that the program is inadequate for the data generated using sandpacks where the high-permeability (as high as 1 Darcy) yields low-capillary pressure (<1 psi). In normal capillary pressure experiments on consolidated cores, the capillary pressure will start at about 1 psi and go higher. The computer program apparently is not capable of handling low-pressure range, and attempts are being made to correct this situation as described in this chapter.

EXPERIMENTAL PROCEDURES

Materials and Equipment

Berea sandstone cores used in this study were obtained from Cleveland Quaries in Amherst, Ohio, and prepared as follows. Unconsolidated sandpacks for use in capillary pressure tests were packed as shown in figure 1 and were made by packing sand in heat shrink teflon tubing which is compressed under 10,000 psi and metal C rings fastened to the end with an additional layer of heat shrink teflon tubing. This has proven to be the best of numerous methods that we have tried in packing high permeability unconsolidated cores for centrifuge capillary pressure/wettability measurements.

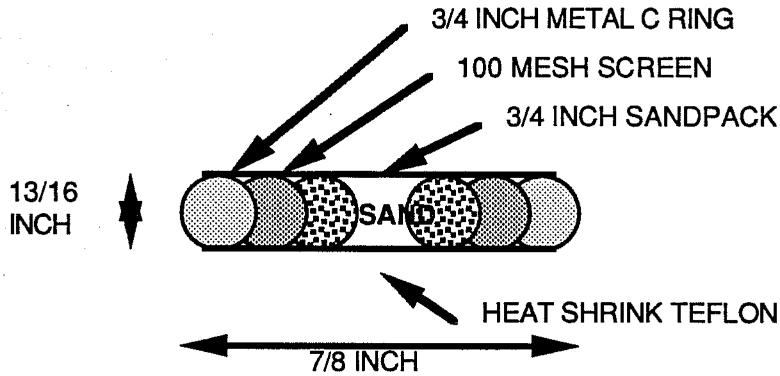

FIGURE 1. - Schematic of core assembly for use of unconsolidated sand in centrifuge determination of capillary pressure and wettability.

Capillary Pressure/Wettability Procedures

The capillary pressure/wettability apparatus and the USBM capillary pressure/wettability method used in this study were previously described.[3]

EXPERIMENTAL RESULTS AND DISCUSSION

Capillary Pressure/Wettability Data Analysis

Since the computer program developed in FY88[2] failed to correctly predict capillary pressures for unconsolidated sandpacks, where capillary pressures are low (lower than 1 psi), a new computer program capable of computing correct capillary pressures over a wide range was developed.

The capillary pressure curve expresses graphically the capillary pressure-wetting phase saturation relationship for a particular rock and is usually determined by the centrifuge technique, a method introduced over 40 years ago by Hassler and Brunner.[4] They developed the following basic equation to calculate fluid saturations from centrifuge capillary pressure measurements.

$$P_{c_i} \overline{S_i} = \cos^2(\alpha/2) \int_0^{P_{c_i}} \frac{S(x)dx}{\sqrt{1 - (x/P_{c_i}) \sin^2(\alpha)}} \qquad (1)$$

where

$$P_{c_i} = \frac{\Delta\rho}{2} \omega^2 (r_e^2 - r_i^2)$$

$$X = \frac{\Delta\rho}{2} \omega^2 (r_e^2 - r^2)$$

$$\text{and } \cos(\alpha) = r_i/r_e$$

Since no analytical solution to equation 1 had been found, Hassler and Brunner differentiated the expression of equation 1 with respect to P_c and truncated the resulting equation to obtain the following:

$$S(P_{c_i}) = \overline{S(P_{c_i})} + P_{c_i}\frac{d\overline{S}(P_{c_i})}{dP_{c_i}} \tag{2}$$

They then solved equation 2 by successive iteration. To improve the accuracy of Hassler and Brunner's scheme, Hoffman[5] derived an expression which was later found to be in error and yielded significantly lower saturations than Hassler's method. Since then, other researchers[6-10] have attempted to derive equations (without Hassler-Brunner's simplifying assumptions) to compute face saturation as a function of capillary pressure. van Domselaar[6] attempted to improve the accuracy of the Hassler and Brunner data-reduction scheme by adding a corrective term to the truncated Hassler-Brunner expression (equation 2). This scheme also was found to be inaccurate and yielded saturations higher than did the traditional Hassler-Brunner approximation.

Since the solution of equation 1 or its variation involves numerical differentiation and integration of experimental data, these data-reduction schemes led to erroneous results because of the accumulation of experimental errors. For these reasons, some researchers have sought methods that avoid the differentiation and integration of experimental data. Bentsen and Anli[7] proposed an alternative approach to the Hassler and Brunner method. They proposed a three-parameter capillary pressure model which has parameters estimated by matching the simulated data with experimental data through a nonlinear regression technique. The NIPER computer program developed in FY88 was based on this model.[3] Christiansen et al.[11] followed an approach similar to that of Bentsen and Anli in that they proposed a four-parameter capillary pressure model that accounted for the radial nature of the centrifugal field.

Unfortunately, because of the lack of flexibility in the assumed functional form for capillary pressure curves, the Bentsen-Anli model yielded incorrect results in many cases. This led researchers to seek a more reliable method for conversion of the experimental data into a capillary pressure curve.[8-10] The most noteworthy among them is that of Rajan[8] who recently presented the following theoretically correct integral equation relating face saturation and capillary pressure:

$$S(P_{c_i}) = \bar{S}(P_{c_i}) + \frac{2R}{1+R} P_{c_i} \frac{d\bar{S}(P_{c_i})}{dP_{c_i}} + \frac{R}{1+R^2} \int_0^{P_{c_i}} \left\{ \frac{1 - \sqrt{1 - \frac{P_c}{P_{c_i}}(1 - R^2)}}{\sqrt{1 - \frac{P_c}{P_{c_i}}(1 - R^2)}} \right\}^2 \frac{d\bar{S}(P_{c_i})}{dP_c} dP_c \qquad (3)$$

Rajan proposed the following scheme to solve equation 3:

(a) fit the observed centrifuge data to an analytical expression; and

(b) numerically integrate equation 3 using the fitted expression.

Ayappa et al.[10] presented a detailed analysis of equation 3 and proposed a finite-element-based solution technique to solve equation 3.

The new computer program developed in this work is based on Rajan's scheme to solve equation 3. As a first step in the data analysis, calculated average saturations at various centrifuge rotational speeds are correlated with corresponding capillary pressures at the inlet face of the core. Much effort has been spent in obtaining a suitable analytical function(s) for the average saturation capillary pressure relationship. Several functional relations were derived using a least-squares regression technique. Although a specific function was entirely satisfactory for a specific set of experimental data, the form proved to be inadequate for other sets of data. To overcome this problem, a set of 12 curves was derived,[12] and the experimental data were fitted to these curves. The unbiased goodnesses of fit (coefficient of determination) for these curves are compared, and the one that yields the best value (greater than 0.98) is selected. This approach has proved to be very satisfactory for the cases tested. The fitted curve is then differentiated analytically and used in solving equation 3. The integration is carried out numerically using an adaptive quadrature technique.

To verify the accuracy of the present solution technique, the following procedure has been used:

(a) The correlation proposed by various researchers was coded, and using an analytical capillary pressure-saturation relationship (equation 4), the accuracy of different methods was established by comparing predicted results with analytical values. Methods compared were those proposed by Hassler and Brunner,[4] van Domselaar,[6] Christiansen et al.,[11] Bentsen et al.[7] and NIPER (Rajan);

$$S = \frac{1.5}{P_C} + 0.25 \text{ for } P_C > 2$$

$$S = 1 \text{ for } P_C \le 2 \qquad (4)$$

(b) next, experimental data were obtained for two unconsolidated sandpacks and one consolidated (Berea) core plug; and

(c) the in-house data were then transmitted to Conoco, and results obtained using their capillary pressure program were compared with those produced from the new program.

Verification of Capillary Pressure/Wettability Data Analysis Program

In figure 2, the computed face saturations using various data-reduction schemes are compared with the theoretical values obtained using equation 4. For the Bentsen and Anli, and Christiansen et al. methods, the following values were assumed for various parameters: S_{wr}= 0.25, P_d = 1.0 psi and σ = 0.75 psi.

Figure 2 shows clearly that for a given capillary pressure, the Hassler and Brunner correlation underestimates the face saturations, while the van Domselaar solution overestimates saturations. The NIPER capillary pressure computer program agrees closely with the analytical value. The integral methods of Bentsen and Anli, and Christiansen correlations start deviating from the theoretical value as the wetting phase saturation approaches the irreducible value. Note that the integral method assumes an apriori functional relationship between the capillary pressure and the wetting phase saturation to fit the capillary pressure curve to the data generated by equation 4. Therefore, using a theoretical capillary pressure curve to generate accurate data, we found that the method based on Rajan's[8] solution (the basis for the NIPER computer capillary pressure data analysis program) matches the theoretical curve more closely than other methods.

In figures 3 and 4, the results predicted using the Conoco program are compared with those predicted using NIPER's program for two unconsolidated sandpacks. The results are in good agreement. In contrast, the old program and numerous other programs calculated values that were an order of magnitude higher from this same set of data.

Core Characterization Studies

Experiments conducted during FY87[1] and FY88[2] showed that increasing temperatures appeared to alter capillary pressures and wettabilities of Berea sandstone in the presence of mineral oil or crude oil. The objective of this phase of research was to determine how higher temperatures affect individual cores and to define the requirements for predicting the effect of temperature on oil recovery for other types of cores. Initial experiments were designed to determine if mineralogical changes or pore geometry were changed significantly in higher temperature capillary pressure experiments with heavy crude oils.

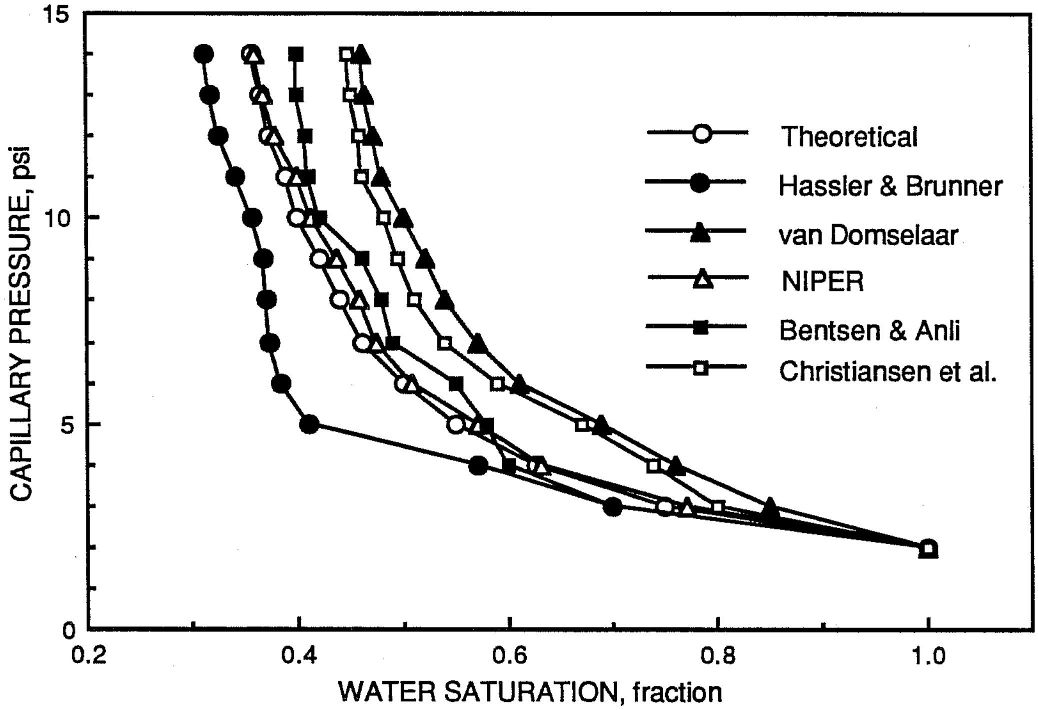

FIGURE 2 - Comparison of capillary pressure curves computed by various methods.

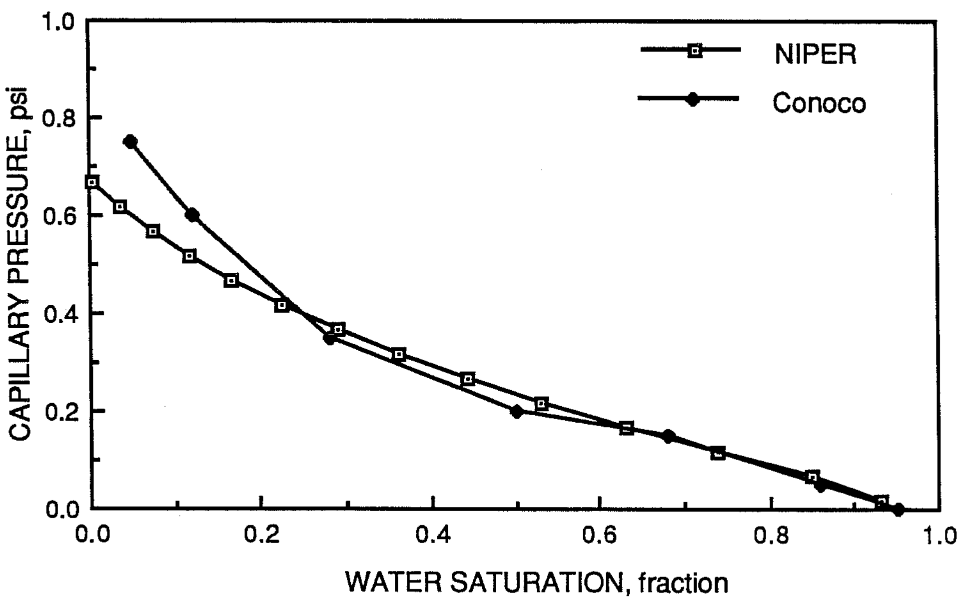

FIGURE 3. - Comparison of centrifuge capillary pressure solution technique - oil displacing brine in unconsolidated sandpack at 200° F - core No. 9.

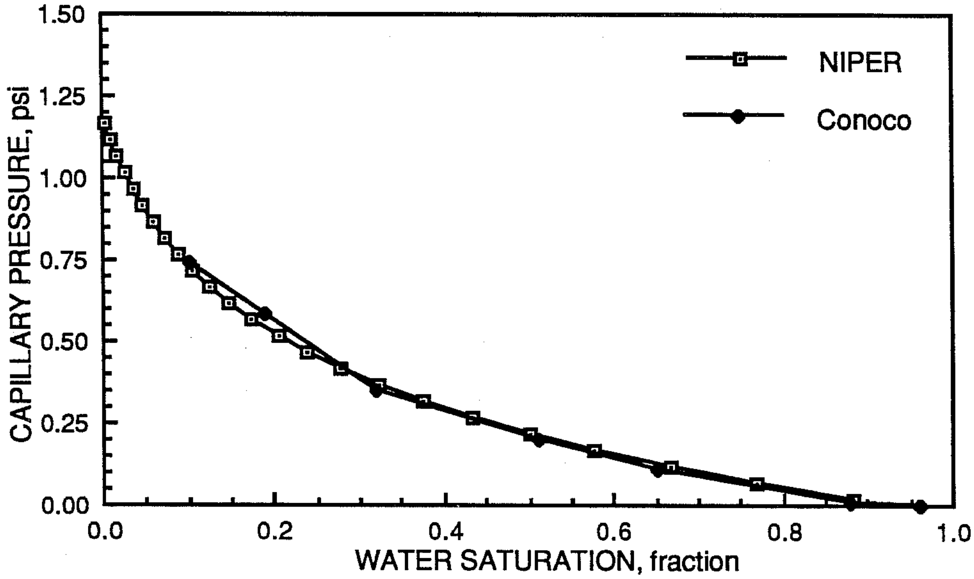

FIGURE 4. - Comparison of centrifuge capillary pressure solution technique - oil displacing brine in unconsolidated sandpack at 200° F - core No. 10.

A literature search made during FY88 indicated that similar work has recently been conducted on the effects of firing on Berea sandstone.[13] In this work, variations of clays, SEM morphology, and pH were evaluated. Since the cores used in this work are heated for 16 hours for equilibrium before each high-temperature capillary pressure/wettability experiment and an additional 8 hours during the centrifuge run, additional evaluations of changes in cores during this time span might provide additional insight as to why changes in capillary pressure and wettability occur.

CONCLUSIONS AND RECOMMENDATIONS

This task was designed to evaluate heavy crude oils using a sandpack. However, time was required to design a system that could operate using a viscous crude and cores that had permeabilities over 1 Darcy. A procedure was developed to yield sandpack cores that were fairly uniform in permeability. The procedures uses a small press to make a core of the appropriate size and permeability. Laboratory evaluations of capillary pressure results from the experiments were initially confusing and were believed to be in error. Extensive evaluations of our old capillary pressure computer program indicated that errors would occur, if total capillary pressure for the run was low (less than 1 psi). These low capillary pressures can be expected for high-permeability cores. A new computer program was developed based on work by Rajan. A set of 12 curves was developed to fit the capillary pressure curves. The unbiased goodnesses of fit (coefficient of determination) for the curves are compared, and the one that yields the best value (greater than 0.98) is selected. This approach has proved to be very satisfactory for the cores tested.

NOMENCLATURE

P_{c_i}	=	Capillary pressure at inlet face of the core, psi
P_c	=	Capillary pressure at any point along the length of a core spinning in a centrifuge, psi
r_i	=	Radius to inlet face from center of rotation, cm
r_e	=	Radius to outlet face from center of rotation, cm
r	=	Radius to any point along the length of the core, cm
R	=	ri/re
S	=	Wetting phase saturation, fraction
$\overline{S}_i$	=	Average wetting phase saturation corresponding to Pci.
$S(P_{c_i})$	=	Wetting phase saturation corresponding to Pci.
$\overline{S}(P_c)$	=	Average wetting phase saturation corresponding to Pc.
S_{wr}	=	Irreducible wetting phase saturation, fraction
ω	=	Angular velocity, radians/sec. = $2\pi n/60$
$\Delta\rho$	=	Density difference between wetting phase and nonwetting phase fluids, g/mL.
σ	=	Capillary pressure normalizing parameter, psi
n	=	Revolutions per minute

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CHAPTER 3. - COMPARISON OF EXPERIMENTAL STEAMFLOOD INFORMATION OBTAINED DURING FY84 THROUGH FY 88 WITH PREDICTED VALUES BASED UPON FUNDAMENTAL PRINCIPLES, TASK 3.

OBJECTIVE

The objective of this task is to compare predicted values with laboratory-measured values of steamflood performance, i.e., develop a thermal numerical simulator to assist in interpretation and planning of laboratory steamflood experiments.

BACKGROUND

There are a number of thermal simulators in the commercial market and some have been developed as part of university research, but a public domain simulator for use in interpreting laboratory results that will run on a personal computer is not available. Most commercial simulators cost >1 million dollars, run computers that are unavailable to this group, and are primarily field oriented. Thus, in cooperation with project BE11A, task 4, a simulator is being developed to assist in laboratory evaluation of thermal oil displacement experiments.

SIMULATOR STATUS AND RECOMMENDATIONS

The description of the simulator under development is described in the companion status report for 1989 Thermal Processes for Light Oil Recovery, project BE11A.[1] The status of the simulator which has been under development since FY88 is such that we have committed to a topical report in September of FY90 describing the model and parameter sensitivity studies.. Along with the simulator development, analysis of the previous years steamfloods has been undertaken to provide test data for the simulator. The analysis has shown that the 2-D physical model is inadequate and needs to be rebuilt as discussed in Chapter 1.

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